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COMPUTATIONAL HYPERSONICS AND PLASMADYNAMICS

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14. ABSTRACT
Several independent efforts addressing simulation capability development and high-speed flow control application were pursued by team members during the reporting period. Control of laminar and turbulent shock/boundary layer and shock/shock interactions was explored with active and passive techniques. Unsteady plasma actuators and laser-based volumetric heat deposition were introduced in ramp and Edney interactions to mitigate integrated and localized heat loads. Separately, porous walls were shown to reduce separation and enhance total pressure recovery in three-dimensional viscous/inviscid interactions. A high-fidelity procedure was developed to couple an unsteady first-principles plasma force model at kilohertz frequencies to full Navier-Stokes solvers. The effect of dielectric barrier discharge-based body forces on excitation of turbulence mechanisms in separated shear layers was investigated. Preliminary simulations were also performed to guide development of a test article for flight testing. State-to-state kinetics simulations were employed to evaluate vibrational bias in dissociation and recombination.

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COMPUTATIONAL HYPERSONICS AND PLASMADYNAMICS

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Abstract

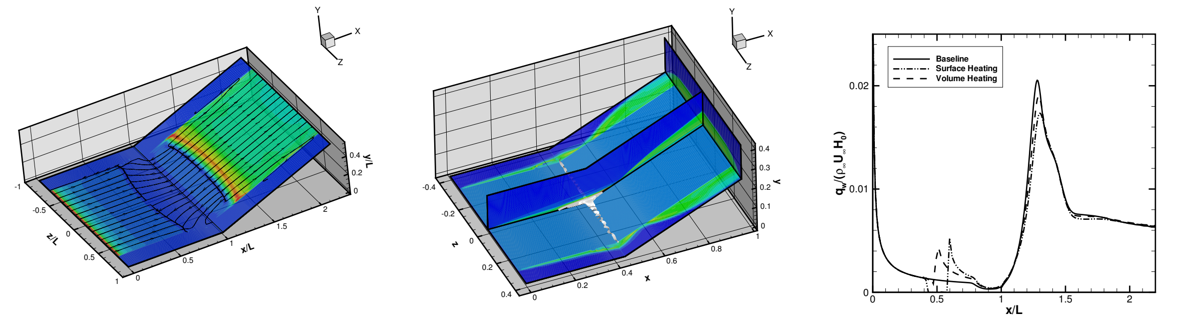
Several independent efforts addressing simulation capability development and high-speed flow control application were pursued by team members during the reporting period. Control of laminar and turbulent shock/boundary layer and shock/shock interactions was explored with active and passive techniques. Unsteady plasma actuators and laser-based volumetric heat deposition were introduced in ramp and Edney interactions to mitigate integrated and localized heat loads. Separately, porous walls were shown to reduce separation and enhance total pressure recovery in three-dimensional viscous/inviscid interactions. A high-fidelity procedure was developed to couple an unsteady first-principles plasma force model at kilohertz frequencies to full Navier-Stokes solvers. The effect of dielectric barrier discharge-based body forces on excitation of turbulence mechanisms in separated shear layers was investigated. Preliminary simulations were also performed to guide development of a test article for flight testing. In the high-temperature regime, state-to-state kinetics simulations were employed to evaluate vibrational bias in dissociation and recombination processes. Team members have continued collaborations with academia within and outside the Summer Faculty and EOARD programs, to continue joint studies on diverse problems including ablation, receptivity, plasma-excitation of nozzle flows and conjugate heat transfer. Basic research transition has also been fostered through active support and monitoring of several continuing and new SBIR/STTR and DARPA efforts.

Objective

This task performs basic research in aeronautical sciences to support Air Force thrusts in sustained hypersonic flight and access-to-space. The main objective is to develop and apply advanced simulation methodologies to understand, predict and control phenomena which establish thermo-mechanical and propulsion related limitations at high-speeds. Particular emphasis is placed on innovative approaches, both for simulation as well as control.

Accomplishments

Shock/shock and shock/boundary layer interactions interactions have a profound adverse impact on various aspects of high speed flight, giving rise to separation, vortical structure formation, thermo-mechanical load peaks, loss of control authority of moving parts and flow distortion. Several different types of techniques, both plasma-based and conventional, were examined for control purposes in ramp and Edney interactions. As an example, elements of thethe flow past a a Mach 14, 24^o compression ramp at $\mathrm{Re}_L = 1.04 \times 10^5$ The skin friction distribution, shown in Figs. 1a and b illustrate the three-dimensional separated flow pattern present in the vicinity of the corner. Plasma actuators were placed in the flow, upstream of the corner, and modeled with steady and unsteady force and heating phenomenological models. Detailed results are presented in Refs. 5 and 6. Selected results for the effect of the heating-based control cases are shown in Fig. 1c. The peak heat transfer rate downstream of reattachment is seen to be reduced for both cases shown, with only moderate changes to the rest of the profile. The mechanics behind the effectiveness of unsteady actuation was also examined. Sample results are shown in Fig. 2 at phase angles of 0% and 60% for the case where a force vector field fluctuating at a frequency of $25kHz$ is oriented outward and upstream. A region of hot, slow fluid, similar in nature to a δ-scale structure in a turbulent boundary layer convects downstream, reducing

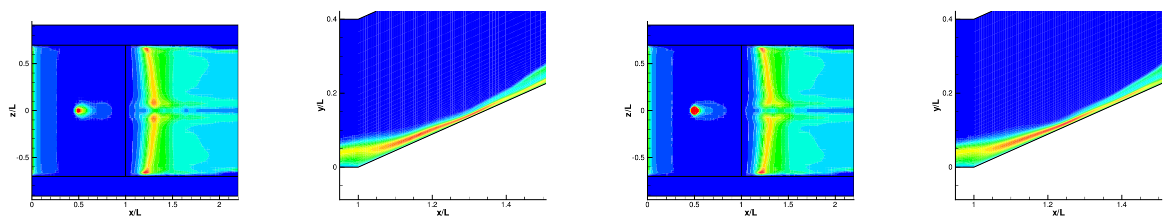


a) Skin friction magnitude and trajectories, baseline flow.

b) Temperature field and selected stream ribbons, baseline flow.

c) Effects of control on wall heat transfer rate.

Figure 1 Results of three-dimensional computations of $24°$ ramp flow.



a) C_h at 0% phase

b) Surface temperature at 0%

c) C_h at 60% phase

d) Surface temperature at 60%

Figure 2 Effect of unsteady actuation. C_h=heat transfer coefficient, T=temperature

the heat transfer rate on its centerline, but at the expense of local hot spots to either side. Analysis of the integrated heat transfer rates indicate that although significant local decreases in heat transfer occur with control, the net heat load remains nearly the same. A counter-rotating, streamwise vortex pair is observed: these reduce peak heat transfer rate by insulating the wall in the reattachment zone.

Passive control with porous walls, enforcing net zero instantaneous mass flux, was also explored for shock/boundary control in both laminar and 3-D turbulent interactions (details may be found in Ref. 12). A sophisticated porous-wall model was adapted to eliminate the need for a separate computational domain in the plenum. Validation studies, presented in Figure 3 for a standing normal shock/boundary layer interaction (SBLI), without and with a 5% porous wall extending the length of the separated region, are clearly excellent. The results indicate that the height of the λ rises due to the disturbance generated by fluid injection into the upstream boundary layer. However, the separation region diminishes in size, consistent with experimental observations. At steady state 1.5% of the incoming boundary layer mass flow is recirculated through the plenum. Porosity reduces skin friction and heat transfer while total pressure recovery is higher due to the weaker λ shock.

The validated procedure was then employed for passive control of the 3-D interaction caused by the double fin configuration, Figure 4a, which has been previously examined in numerous studies. Figure 4b and the top part of Fig. 4d depict results for the uncontrolled interaction. The complicated flow structure has been described in terms of major regimes including a separated boundary layer, centerline vortex pair, vortex interaction and entrainment flow. The surface oil flow has been previously validated by comparison with experimental data. Several lines

a) Problem examined

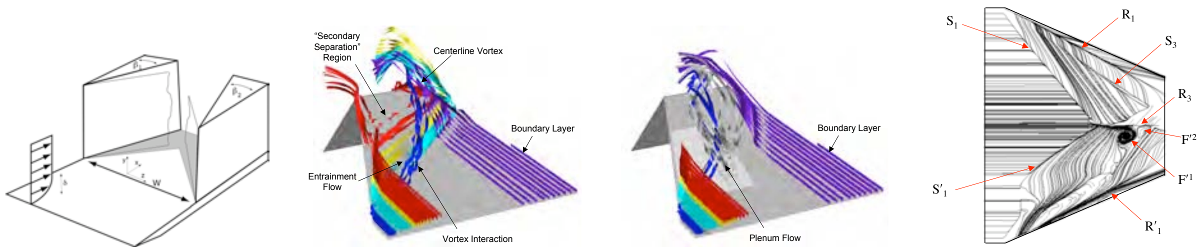
b) Experiment - no control

c) Simulation - no control

d) Experiment - porous wall

e) Simulation - porous wall

Figure 3 Validation of porous wall simulation on normal SBLI



a) Schematic

b) Solid Wall

c) Porous Wall

d) Surface flow (top: no-control, bottom: porous-wall)

Figure 4 Porous wall control of 3-D turbulent SBLI

of coalescence and divergence are evident, marked S and R respectively. The porous wall, of porosity 40% is assumed to span the foot of the 3-D λ structure (lightly shaded region in Fig. 4c). The porous wall essentially injests the main regimes, but the extent of the disturbed region between the primary lines of coalescence and divergence increases (lower part of Fig. 4d). The pressure near reattachment (not shown - see Ref. 12) is reduced as is peak heating near the symmetry plane. However, the λ shock is broadened and the triple point moves away from the plate, similar to the observation in 2-D control. This generally weaker interaction yields an overall improvement in pressure recovery.

Advanced numerical approaches to couple first-principles dielectric barrier discharge models to the full Navier-Stokes equations were also successfully developed. Subsequently, these were employed to explore the manner in which momentum injected into the flow by the body force influences fluid instabilities yielding a powerful lever to enhance plasma actuator effectiveness. The simulation complexity arises from both the daunting computational requirements of 3-D turbulent simulations at plasma time scales as well as gaps in current understanding of the molecular processes that dominate charged particle generation and behavior. Thus, a coupled approach, shown in Fig. 5, is the most effective. Specifically, the force field due to the device, Fig. 5a, is obtained for a small region surrounding the device, including the dielectric region beneath the surface (Fig. 5b). This sophisticated multi-fluid collisional plasma calculation, obtained from Prof. S. Roy of Kettering University, has been described in Ref. 15 and others. The force field at a sample phase angle is shown in Fig. 5c. The variation is stored at many phase angles of excitation and transferred through rotation and scaling operations (Fig. 5d) to the appropriate point on the wing section, usually slightly downstream of separation, Fig. 5e. The area-weighted procedure to ensure that the integrated force and gradients are matched has been described in Refs. 19, 24, which also describes the spatio-temporal coupling methodology.

The approach was employed, together with a highly accurate scheme, to examine numerous aspects related to the control of a stalled flow past a wing section at a nominal Reynolds number of $45,000$ and angle-of-attack of 15^o. The baseline flow is depicted in Fig. 5f with iso-levels

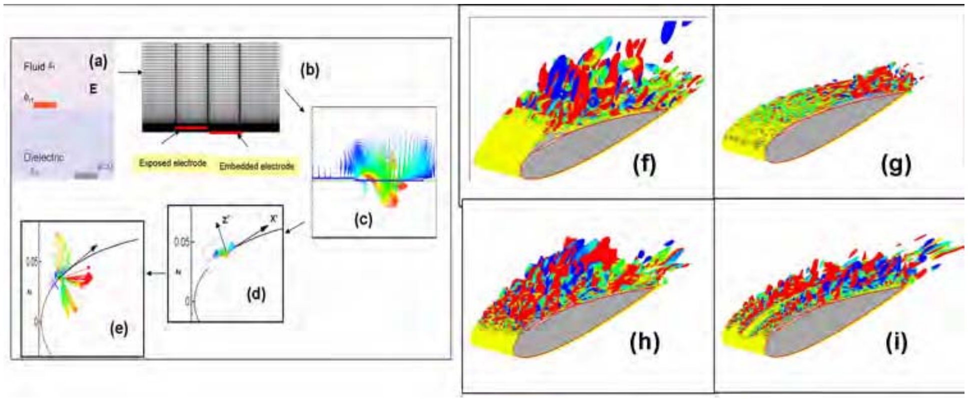


Figure 5 Coupling of first principles plasma and fluid procedures for wing-section stall control

of instantaneous vorticity magnitude colored by the spanwise component of vorticity. A shear layer emanates from the separation point, which occurs at approximately 2% chord. Proceeding downstream, transition sets in and the layer loses its coherence as the three-dimensional break-up process progresses. It has been shown previously that the absence of a spanwise breakdown mechanism in 2-D necessitates a full 3-D analysis.

Qualitative differences between the effects of the controlled unsteadiness associated with the radio-frequency excitation versus that due to duty cycles (encapsulating a steady phenomenological force field) have been examined. Details may be found in Ref. 24. The effect of an actuator extending the entire span with a peak strength of 2400 (ratio of electrical to inertial force) – similar to that employed with the phenomenological model - is shown in Fig. 5g. Transitional streamwise oriented structures are evident which persist to near the point of maximum thickness, at which point turbulence sets in relatively rapidly. Force fluctuations evidently trigger turbulence, together with an acoustic signal which cannot be represented accurately by the steady phenomenological model. Results obtained when the actuator strength is reduced to 250 are shown in Fig. 5h. In this case, the striations observed previously do not occur. However, the breakdown is more rapid with excitation, and the size of the separation region is considerably reduced. The flow field obtained with the finite-span actuator ($D_c = 2400$) is shown in Fig. 5i. Similar longitudenal structures are observed as for the full span case. However, at the spanwise edges of actuation, instabilities are noted to set in very rapidly. The region of chaotic flow spreads towards the center of the section and after about mid-chord, the flow is turbulent on the entire span. Examination of the mean flowfield reveals the presence of a central region near the actuator characterized by a shallow high-speed jet-like structure of high-vorticity flanked by coherent vortical regions that entrain fluid. Diffusion of these structures is accelerated following the onset of turbulence. The flowfield near the leading edge is consistent with the development of a horse-shoe vortex, with a core that wraps around the actuator yielding a streamwise vortex pair that diffuses with the onset of turbulence. Numerous other results, including comparison with duty cycles of different inter-pulse periods have been described in Ref. 24.

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Personnel

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Publications - July 2005-Present

1. Poggie, J., "Numerical Simulation of DC Glow Discharges for High-Speed Flow Control," submitted for special issue of the Journal of Propulsion and Power, 2006.
2. Chatterjee, K. and Poggie, J. "A Parallelized 3D Floating Random-Walk Algorithm for the Solution of the Nonlinear Poisson-Boltzmann Equation," Progress in Electromagnetics Research, Vol. 57, pp. 237-252, 2006.
3. Chatterjee, K. and Poggie, J. "A Two-Dimensional Stochastic Algorithm for the Solution of the Nonlinear Poisson-Boltzmann Equation: Validation with Finite Difference Benchmarks," International Journal of Numerical Methods in Engineering, Vol. 66, pp. 72-84, 2006.
4. Poggie, J. "Numerical Simulation of DC Glow Discharges for High-Speed Flow Control," International Workshop on Thermochemical Processes in Plasma Aerodynamics, St. Petersburg, Russia, June 2006.
5. Poggie, J. "Plasma-Based Hypersonic Flow Control," AIAA Paper 2006-3567, 37th AIAA Plasmadynamics and Lasers Conference, June 2006.
6. Poggie, J. "Plasma-Based Control of Shock-Wave/Boundary-Layer Interaction," AIAA Paper 2006-1007, 44th AIAA Aerospace Sciences Meeting, January 2006.
7. Josyula, E. and Xu, K. "Nonequilibrium Relaxation in High-Temperature Gas Flows," Computational Fluid and Solid Mechanics 2005, K.J. Bathe (Editor), Elsevier Ltd.
8. Josyula, E., Xu, K. and Wadsworth, D., "Testing Continuum and Non-Continuum Descriptions in High Speed Flows," Rarefied Gas Dynamics: 24th International Symposium, 2005, M. Capitelli (Editor), American Institute of Physics.
9. Xu, K. and E. Josyula, "Multiple Translational Temperature Model and its Shock Structure Solution," Physical Review E, Vol. 71, 2005, American Physical Society.
10. Josyula, E., Bailey, W.F. and Gudimetla, V.S.R. "Modeling of Dissociation in Nonequilibrium Hypersonic Flows," AIAA 2006-3421, Joint Thermophysics and Heat Transfer Conference, June 2006, San Francisco
11. Croker, B.A. and McMullan, R.J., "Development of a High Order Shock Capturing Algorithm using Compact Differencing," AIAA Paper 2005–4699, Toronto, Canada.
12. Croker, B.A., "Numerical Investigation of 3-D Swept Shock Interaction Control with Porous Surfaces," AIAA Paper 2006-3346, San Francisco, CA, 2006.
13. Gaitonde, D.V. and Lindsey, M.F., "Development of Plasma-based Flow Control Techniques for Scramjet Flow Paths," DoD HPC Users Group Conference, Denver, CO, Jun, 2006.
14. Shang J.S., Surzhikov, S.T., Kimmel, R., Gaitonde, D., Menart, J., Hayes, J., "Mechanisms of Plasma Actuators for Hypersonic Flow Control," Progress in Aerospace Sciences, Vol. 41, 2005, pp. 642-668.
15. Roy, S. and Singh, K.P. and Gaitonde, D.V., "Dielectric Barrier Plasma Dynamics for Active Control of Separated Flows," Applied Physics Letters, Vol. 88, No. 121501, 2006
16. Gaitonde, D.V. "Exploratory Study of the MHD Energy-Bypass Procedure in a 3-D Scramjet," Accepted for publication, Journal of Propulsion and Power, 2006
17. D.V. Gaitonde, "Effect of Hall-Currents on Simulated 3-D Scramjet with MHD Bypass," Accepted for publication, Journal of Propulsion and Power, 2006
18. D.V. Gaitonde, "High-Speed Flow Control Analyses with 3-D Magnetohydrodynamic Simulations," Review Article, submitted to Journal of Propulsion and Power.
19. Gaitonde, D.V., Visbal, M.R. and Roy, S. "A Coupled Approach for Plasma-Based Flow Control Simulations of Wing Sections," AIAA Paper 2006-1205, Reno, NV, Jan, 2006.
20. Yan, H. and Gaitonde, D. "Control of Edney IV Interaction with Energy Pulse," AIAA Paper

2006-0562, Reno, NV, Jan. 2006.
21. Visbal, M. and Gaitonde, D.V., “Control of Vortical Flows Using Simulated Plasma Actuators,” AIAA Paper 2006-0505,Reno, NV, Jan 2006.
22. Roy, S., Singh, K.P., Kumar, H., Gaitonde, D.V. and Visbal, M., “Effective Discharge Dynamics for Plasma Actuators,” AIAA Paper 2006-0374, Reno, NV, Jan 2006.
23. Yan, H. and Gaitonde, D.V., “Effect of Energy Pulse on Edney IV interaction”, AIAA 2006-3344, San Francisco.
24. Gaitonde, D.V., Visbal, M.R. and Roy, S., ”Three-Dimensional Plasma-Based Stall Control Simulations with Coupled First-Principles Approaches,” FEDSM2006-98553, 2006 ASME Summer Meeting, Miami, FL, 2006.
25. Roy, S., Singh, K., Kumar, H., Gaitonde, D. and Visbal, M.R., “Effective Discharge Dynamics for Plasma Flow Control,” AIAA Paper 2006-3074
26. Roy, S. Singh, K. and Gaitonde, D.V., “Dielectric Barrier Plasma Dynamics for Active Control of Separated Flows,” Appl. Phys. Letters, Vol. 88, No. 121501, 2006.
27. Visbal, M., Gaitonde, D. and Roy, S., ”Control of Transitional and Turbulent Flows using Plasma-Based Actuators,” AIAA Paper 2006-3230, June, 2006.
28. Malo-Molina, F.J., Gaitonde, D.V., Ebrahimi, H.B. and Ruffin, S., ”Numerical Simualtion of a Generic High-Speed Inlet/Combustor,” AIAA Paper 2006-4683, Joint Propulsion Conference, Sacramento, CA, 2006.
29. Malo-Molina, F.J., Gaitonde, D.V., Ebrahimi, H.B. and Ruffin, S., ”Analysis of an Innovative Inward Turning Inlet Using an Air-JP8 Combustion Mixture at Mach 7,” AIAA Paper 2006-3452, 36th AIAA Fluid Dynamics Conference, San Francisco, CA, 2006.

Extramural Interactions and Awards

- Honors and Awards: Benjamin D. Foulois Award for Basic Research, AFRL/VA, 2006 (Poggie), Special Act Award (Poggie), AIAA Outstanding Technical Achievement Award (Poggie). AFOSR Star Team Award. Applied Aerodynamics Best Paper Award, 2006 (Visbal and Gaitonde).
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- Activities: Members of technical committees Plasmadynamics (Poggie), Thermophysics (Josyula), Fluid Dynamics (Croker and Gaitonde), Air Breathing Propulsion (Gaitonde). AIAA Progress Series in Astronautics and Astronautics Editorial advisory board (Josyula), AIAA Journal Associate Editor (Gaitonde). Technical program chair: AIAA Thermophysics Conference, ASM 2006 (Josyula), Plasmadynamics and Lasers Conference, ASM 2007 (Poggie. Reviewers numerous Journals and conferences (session chairs), AFOSR and ARL proposals. proposals.